

INTRODUCTION TO SMOOTH MANIFOLDS

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Exercise 1.1. Show that equivalent definitions of manifolds are obtained if instead of allowing U to be homeomorphic to *any* open subset of \mathbb{R}^n , we require it to be homeomorphic to an open ball in \mathbb{R}^n , or to \mathbb{R}^n itself.

Proof. It is clear that a “manifold” satisfying the open-ball or \mathbb{R}^n definition satisfies the open-subset definition. Let M be a manifold satisfying the open-subset definition. Let $x \in M$ be given and let U, \hat{U}, ϕ be given according to the definition. Since \hat{U} is open, there exists an open ball B such that $\phi(x) \in B \subset \hat{U}$. Restrict ϕ to $\phi^{-1}(B)$. Then $\phi^{-1}(B)$ is an open subset of M containing x , and $\phi|_{\phi^{-1}(B)}$ is a homeomorphism between $\phi^{-1}(B)$ and B . Thus M satisfies the open-ball definition.

$B(x, r) \subset \mathbb{R}^n$ is homeomorphic to \mathbb{R}^n by the map $(x_1 + a_1, \dots, x_n + a_n) \mapsto (\frac{a_1}{r-a_1}, \dots, \frac{a_n}{r-a_n})$ where $x = (x_1, \dots, x_n)$ is the center of $B(x, r)$ and r is the radius. Since the composition of two homeomorphisms gives a homeomorphism, M also satisfies the \mathbb{R}^n definition as well. \square

Exercise 1.6. Show that \mathbb{RP}^n is Hausdorff and second-countable, and is therefore a topological n -manifold.

Proof. From the definition of π , it is easy to see that $\pi(B(x, r))$ is open in \mathbb{RP}^n where $x \in S^n$ and $0 < r < 1$.

Let $[x], [y] \in \mathbb{RP}^n$ be given. Without loss of generality, assume $x, y \in S^n$. Let $r = \min\{|x - y|, |x + y|, 1\}/2$. Then $U_x = \pi(B(x, r)), U_y = \pi(B(y, r))$ contain $[x], [y]$, respectively. $\pi^{-1}(U_x), \pi^{-1}(U_y)$ are both open in $\mathbb{R}^{n+1} \setminus \{0\}$ which can be seen easily by writing down exactly which points belong to them, so U_x, U_y are both open in \mathbb{RP}^n . Then $\pi^{-1}(U_x \cap U_y) = \pi^{-1}(U_x) \cap \pi^{-1}(U_y) = \emptyset$, so $U_x \cap U_y = \emptyset$. Therefore, \mathbb{RP}^n is Hausdorff.

Let $\mathcal{B} = \{\pi(B(x, 1/k)) \mid x \in \mathbb{Q}^{n+1} \cap S^n, k \in \{2, 3, 4, \dots\}\}$. Then \mathcal{B} is a countable collection of open sets whose union is \mathbb{RP}^n . Let $U \subset \mathbb{RP}^n$ be a nonempty open set. Let $[x] \in U$. Since π is a quotient map, $\pi^{-1}(U)$ is open. Moreover, $x \in \pi^{-1}(U)$. Without loss of generality, $x \in S^n$. Then $x \in B(x', 1/k) \subset \pi^{-1}(U)$ for some $B(x', 1/k) \in \mathcal{B}$. Then $[x] = \pi(x) \in \pi(B(x', 1/k)) \subset \pi(\pi^{-1}(U)) = U$. Therefore, \mathcal{B} is a countable basis of \mathbb{RP}^n . \square

Exercise 1.7. Show that \mathbb{RP}^n is compact.

Proof. $\pi(S^n) = \mathbb{RP}^n$ and S^n is compact because it is a closed, bounded subset of \mathbb{R}^{n+1} . (Heine-Borel) Moreover, the image of a compact set under a continuous map is compact. (See A.45(a)) Thus \mathbb{RP}^n is compact. \square